Design rules for vacuum chambers

C. Hauviller
CERN, Geneva, Switzerland

Abstract
Producing a vacuum chamber means defining the boundary conditions (inner and outer envelopes, operational constraints, etc.), choosing the material, designing the parts, manufacturing and assembling these parts together and putting them under vacuum. This paper gives the methodology, methods and hints for designing vacuum chambers.

1 Introduction

The first step in the mechanical design of a vacuum chamber is to clearly define what all the boundary conditions are and often this is not the easiest part of the job since most of the parameters are settled by the other systems making up the equipment, in the large sense, to be built. The vacuum chamber arrives late and should simply fit in what is left!

The material is a subject of long debate, still alive, even for 'usual' types of equipment.

The initial phase, the conceptual design, which usually does not need accurate studies, is followed by the detailed design, the latter strongly associated with the manufacturing, itself controlled by a quality assurance plan.

This paper on mechanical design is intended to go through all the steps mentioned above. It is difficult to be exhaustive and we shall not be, since what we deal with will be related not only to accelerator equipment on the beam lines but also to other vacuum vessels for services such as cryogenics. However, the vacuum vessels we consider are static, the ones which move being subject to specific rules not presented here.

Methodology, methods, and hints will be given, but consultation of some of the references is a must if you have to design such a system yourself. References on general mechanical design are not quoted here since there are many. Reference [1] from the 1999 CERN Accelerator School on Vacuum Technology could be very useful.

It is also important to remember that a classical rule, valid for any type of equipment, is that more than 70% of the final cost is already defined at the end of the design phase. Investing more during the initial phase is always rewarding!

2 Boundary conditions

2.1 Environment

To determine the environment is clearly the first step. The sub-sections are not necessarily exhaustive, but the list of physical phenomena influencing the design of vacuum chambers is probably complete.

2.1.1 Outside

If the external envelope is simply the volume where the chamber will sit, the situation should not be very difficult when it is located inside a large building, but fitting a vacuum chamber/beam pipe of a particle accelerator inside an optimized gap of magnets may be much more constraining. Adequate space for supports will inevitably simplify the design of the chambers. In addition, space and access to the pumping ports and to the pumping and diagnostics equipment could also be very restricted leading to stringent consequences on the operation.

Make sure that you give your requirements before it is too late.

2.1.2 Inside

The beam envelope is the main parameter for the vacuum chamber of an accelerator, but the conductance is another one in case of lumped pumps: the pressure distribution between two pumping ports is parabolic and the maximum value of this parabola defines the operating pressure. Distributed pumping is a solution, at least partially. For a cryogenic system, the inner piping and its insulation layers define the inner envelope, but do not forget to include extra space to allow for the movements resulting from pressure and temperature variations.

2.1.3 Pressure and forces

The differential pressure on a vacuum chamber is obviously one bar during operation but it is recommended to check what all the intermediate steps are like, for example, an over-pressure test for qualification. In the presence of a closed end, the resulting forces could be large and the design should take into account the transmission of these forces to the fixing points through the vacuum chamber wall.

2.1.4 Temperature

Specifying operating temperature (usually room temperature), bake-out temperature (usually between 150ºC and 300ºC), and exceptional temperature in the case of an incident (like a cool-down due to cryogen losses) together with all the transitories is a must. The effects of temperature are dilatations, stresses and changes of material properties and they may have destructive effects if badly mastered. Slow temperature transients allow the resulting stresses to be minimized but it becomes an operational constraint that is not necessarily acceptable.

2.1.5 Specific cases

To be complete, one should go through cases of vacuum chambers submitted to specific constraints or dedicated to special applications.

Important local heat loads, like synchrotron radiation, should be evacuated through good thermal conducting materials. Electrical impedance is reduced with a good electrical conductivity but, on the other hand, non-conducting material is required for electric isolation.

Activation of material by the particles hampers the functioning of the equipment, delaying access to an accelerator after switching off and producing radioactive components that are delicate to handle. Elements with long half-lifetime must be avoided in the materials in order to reduce the activation level and minimize the decay time.

Should particles inside the vacuum chambers escape, either as a secondary beam going through a window to reach targets or generated by collisions and to be analysed by surrounding detectors, the parameters defining the transparency to particles, the radiation length (X_0), and the collision length must be considered.

2.2 Materials

Choosing the material for a vacuum chamber often leads to wide discussion of their principal properties. The material parameters design for the vacuum chamber in terms of mechanics could be quite numerous, but there are only three main ones: the modulus of rigidity (Young's modulus: E), the elastic ($\sigma_{0.2}$) and rupture (σ_r) limits.

These parameters are usually easily available for any material. A simple analysis of traction/compression tests is a common practice. Figure 1 shows a typical shape of traction curves of metallic materials. It shows how to define the yield or elastic limit. The modulus of rigidity is obtained through the value of the slope of the quasilinear part of the curve.

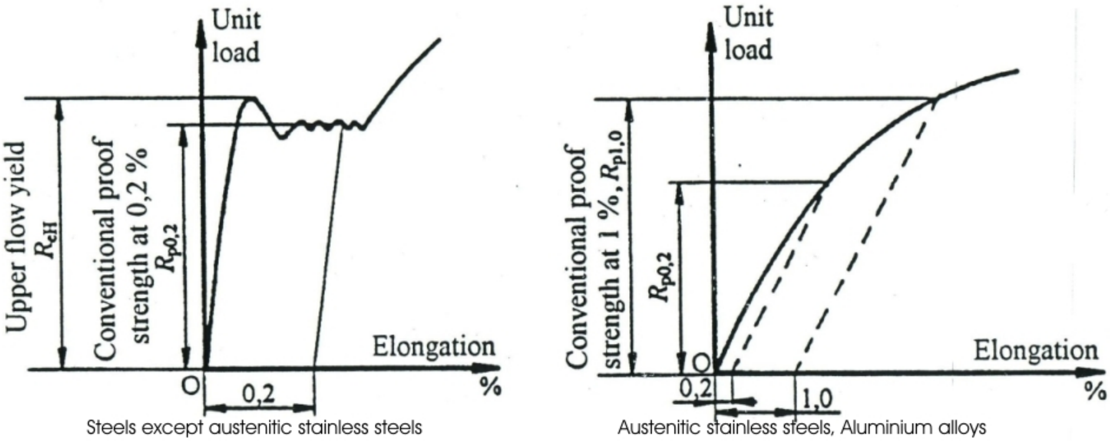

Fig. 1: Traction curves of metals

More sophisticated tests like biaxial ones are required only for very specific cases.

Other parameters like creep data, fatigue limit, fracture toughness could be useful for specific design but usually complicate the choice of material. These parameters decrease when the temperature increases, creep weakens the material and, as a rule of thumb, the upper temperature limit of usage of a metal is 70% of its melting temperature in degrees kelvin.

Another factor not to be forgotten is the vapour pressure which depends upon the temperature and the pressure. Materials like zinc, cadmium or magnesium, or standard resins which have significant vapour pressure at low temperature are not acceptable when a bake-out is foreseen.

Selection of materials for specific cases is a multi-parameters problem. It can be eased by the use of non-dimensional parameters [2]. These have been used for the specific type of vacuum chambers, which is the beam pipes for the experiments installed in colliders [3], LEP [4], the LHC [5]. As mentioned above, they should be transparent to particles. It has been shown that the selection can be based on the non-dimensional parameter ($X_0E^{1/3}$) that gives a figure of merit for the materials (Table 1) and, for this specific case of beam pipes, beryllium and carbon fibre composite outrun by a large factor aluminium, titanium, and steel.

Table 1: Figures of merit of materials in terms of transparency

	Be	**CFC**	**Al-Be**	**Al**	**Ti**	**Fe**
E (GPa)	290	200	193	70	110	210
X_0 (m)	0.353	0.271	0.253	0.089	0.036	0.018
$X_0E^{1/3}$	2.34	1.58	1.46	0.37	0.17	0.11

A good electrical or thermal conductivity could be required or banished. Copper and aluminium are the usual candidates for the former case and ceramics, like aluminium oxide, for the latter one.

Recent major advances in metallurgy and surface physics allow the creation of more optimized material which exhibits specific properties. The plain material is replaced by a combination of materials, each with a specific function with a better physical parameter. Two examples among many combinations are the adjunction of a layer of a conductive material (copper) on a structural material (stainless steel) and, as a barrier to gas diffusion, a thin layer of aluminium on a structural material (carbon fibre composite).

Besides the physical characteristics, specific technological properties should not be forgotten. Leak tightness of a vacuum chamber is a must but this may be difficult to obtain if the weldability of the material is poor and leads to the use of sophisticated and expensive techniques.

Cost is the final criterion. Besides the material quality, in particular the cleanliness in terms of inclusions and impurities required and that one cannot necessarily afford on a large scale, the availability is a predominant factor. It is strongly recommended to favour materials of general use in industrial application.

Raw material is not the single parameter for the cost criterion since a complex and expensive manufacturing process could totally hamper the final cost. But machining could be efficient and fast and therefore cheap, although a large amount of costly raw material is lost as chips. Moreover the precision required for a welded part could need expensive tooling not included in the initial estimate.

The most common materials are austenitic stainless steel (316LN, 316L, 304L), aluminium alloys (5000 and 6000 series) and copper (OFHC, Glidcop).

2.3 Legislation and codes

It is quite difficult to define a clear basis for the regulations to be applied to the design and construction of vacuum chambers. These vacuum chambers are generally special but they should behave properly and should be safe. It is important that guidelines at least should be provided. But this is not strictly the case since, to the knowledge of the author, no construction code dedicated to vacuum vessels exists but there is one for cryogenic vessels.

One's own regulations should therefore be applied and the common practice is to treat a vacuum chamber as a pressure vessel with some arrangements. This is in particular the case at CERN with the Safety Code D2 for pressure vessels and pressurized pipelines [6].

European legislation is now based upon directive 97/23/EC of the European Parliament and of the Council of 29 May 1997 on the approximation of the laws of the Member States concerning pressure equipment. "This directive applies to equipment subject to a maximum allowable pressure exceeding 0.5 bar" which "does not pose a significant hazard".

Based on this directive, standards, so-called norms or codes, are being prepared by qualified and specialized European and national bodies. They are intended to define common rules accepted by clients, manufacturers, technical centres, and inspection bodies.

These construction/safety codes have been developed for decades, before directive 97/23/EC, and are quite similar to each other and also to other international standards. These thick documents generally contain rules for materials, design, manufacturing, inspection and testing, certification of pressure vessels, including those submitted to external pressure.

The classical ones are:

– CODAP 2005, French code for construction of unfired pressure vessels issued by the Syndicat National de la Chaudronnerie, de la Tôlerie et de la Tuyauterie industrielle (SNCT) [7];

– EN 13445, Unfired pressure vessels issued by the European Committee for Standardization (CEN) [8];

– 2004 BPVC, Boiler and Pressure Vessels Code, Section VIII – Rules for Construction of Pressure Vessels, issued by the American Society of Mechanical Engineers (ASME).

There should also be a special mention for the European standard EN 13458-2 [9] which treats specifically the “static vacuum insulated vessels” of the “cryogenic vessels” in a way very similar to the codes mentioned above.

3 Design

3.1 Basics

Stresses generated by the loads enumerated before should usually remain in the elastic range. This means that the equivalent stress (according to the Von Mises or Tresca criterion for example) should not exceed the elastic limit ($\sigma_{0.2}$) anywhere in the structure. The directive 97/23/EC states in particular that “the permissible membrane stress for predominantly static loads…must not exceed…2/3 of the yield limit (stainless steel and aluminum alloys)”.

But, vacuum usually corresponds to an external pressure and the resulting membrane stresses are compressive. Under these conditions, the membrane strain energy can be converted to bending strain energy, leading to an instability and a bifurcation point on the behavioural curve, a potential buckling (Fig. 2). Buckling is a non-linear phenomenon and it could be strongly influenced by the defects inherent to the manufacturing.

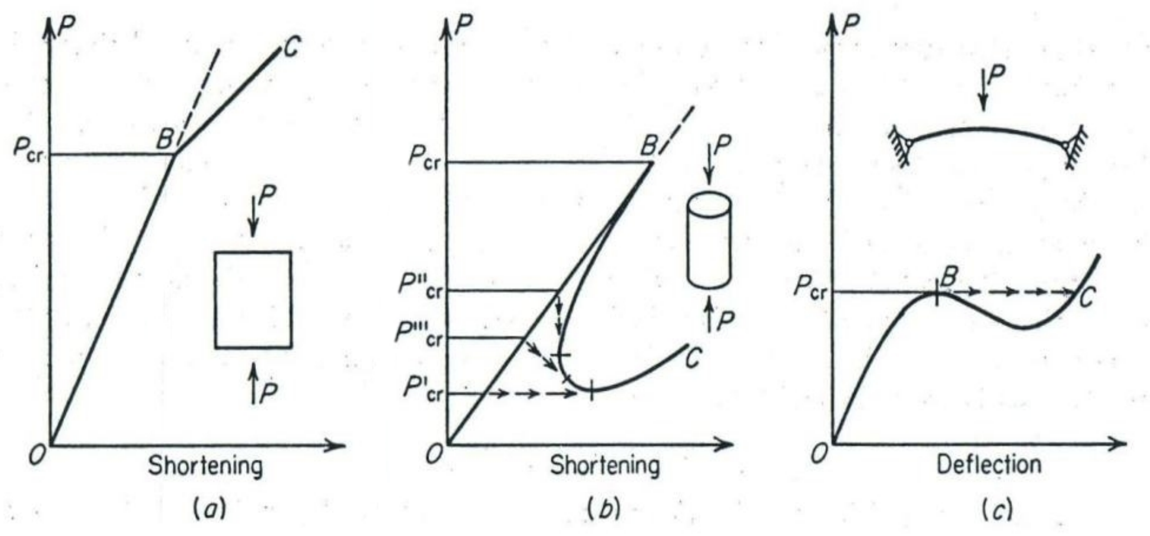

Fig. 2: Buckling behaviours

A safety factor must be applied to any computed buckling value: pressure vessel codes like CODAP use 3.0 but EN 13458-2 quotes only 2.0 for outer jackets.

In fact, in practice, it is quite easy to elaborate a design to stay in the elastic range of a material but buckling, a phenomenon factor, could be more difficult to deal with.

3.2 Methods and techniques

In the pre-design phases and when checking the final design, somewhat simple analytical methods could be more efficient than structural analysis programs. They permit a quick analysis of the effects of various geometrical parameters. Some of them will be quoted below.

However, the use of structural analysis packages, usually based on the Finite-Element Method (FEM) is a must for the detailed design of vacuum vessels. Two main families of elements ought to be used for these computations (Fig. 3): the solid elements for the 'thick' machined parts but the shell elements are more efficient for thin shell structure (t/R < 100). In the shell elements, the through-thickness stresses are assumed linear and integrated in membrane (constant term) and bending (linear term).

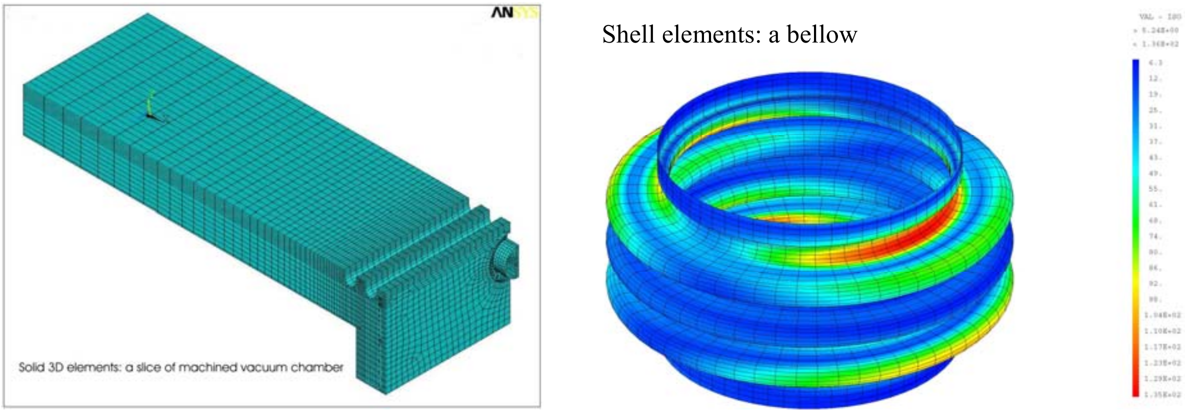

Fig. 3: Finite element models

The first step of the analysis is the linear elastic one which gives all the information on a structure: displacements, strains, and stresses. The second step is to search for buckling factors for the main modes (search for linear eigenvalues). A third one could be useful for thin shells where the non-linear pre-buckling analysis allows one to determine the shake-down factor on the linear buckling value; it could be as high as 10 for very thin shells.

3.3 Tubes

Tubes are obviously the most common shape for vacuum chambers.

The most stable ones are circular ones for which a quick analysis is quite straightforward.

The circumferential stress under external pressure p is simply:

$$\sigma_\theta = \frac{pR}{t} \,, \tag{1}$$

R and t being, respectively, the radius and the thickness of the circular tube.

If the tube is closed and subjected to an axial force F, the axial stress is

$$\sigma_z = \frac{pR}{2t} + \frac{F}{2\pi Rt} \tag{2}$$

and the Von Mises equivalent stress to be compared to the material maximum allowable stress is

$$\sigma_e = \frac{1}{2}\left[3\left(\frac{pR}{t}\right)^2 + \left(\frac{F}{\pi Rt}\right)^2\right]^{\frac{1}{2}} . \tag{3}$$

The buckling pressure can also be computed through analytical formulas, depending upon the geometrical parameters of the tube and the Young's modulus of the material. The most conservative one is for an infinite length of the tube:

$$p_{\mathrm{cr}} = \frac{0.25E}{1-\nu^2}\left(\frac{t}{R}\right)^3 , \tag{4}$$

ν being the Poisson ratio and $(1 - \nu^2)$ could be generally approximated by 0.9.

A rule of thumb is that the thickness of a stainless-steel circular tube should be at least one hundredth of its diameter (safety factor included).

A non-circular tube is more difficult to quickly estimate. However, quasi or approximately rectangular shapes can be approximated by plates or simply by beams (width of a unit length) either clamped or simply supported.

If approximated by a beam, the maximum deflection (w_{max}) and stress (σ_{max}) (upper and lower bounds) are

$$\frac{1}{32}\frac{pl^4}{Et^3} < w_{\mathrm{max}} < \frac{5}{32}\frac{pl^4}{Et^3} \tag{5}$$

$$\frac{1}{2}p\left(\frac{l}{t}\right)^2 < \sigma_{\mathrm{max}} < \frac{3}{4}p\left(\frac{l}{t}\right)^2 \qquad \text{(not at the same location)} , \tag{6}$$

l and t being, respectively, the span and the thickness of the tube.

Specific analytical programs have been developed to treat elliptical tubes.

3.4 Windows

Special care is required for these critical items. Designed to allow particle beams to escape the vacuum chambers without interaction, windows are thin and often manufactured with a special material.

The best shape for resisting external pressure is a spherical dome but the manufacture is difficult and the external ring must be quite rigid. If the window is oriented in such way that it can buckle, the classical buckling pressure is

$$p_{\mathrm{CL}} = \frac{2E}{\sqrt{3\left(1-\nu^2\right)}}\left(\frac{t}{R}\right)^2 , \tag{7}$$

R and t being, respectively, the radius of curvature and the thickness of the spherical dome.

A flat window is the other common option but, when put under pressure, the deflection (w_{max}) is not negligible

$$w_{\mathrm{max}} = \frac{3}{16}\frac{p}{E\left(1-\nu^2\right)}\frac{R^4}{t^3} , \tag{8}$$

R and t being, respectively, the radius and the thickness of the circular window.

Non-circular windows exhibit high loads concentrated in the corners somewhat difficult to treat in case of a weld and a source of nightmares when clamped inside flanges.

3.5 Bellows

Bellows are another critical item which provide the capacity to minimize stresses due to displacements during commissioning and operation and to ease assembly of misaligned parts. Designed to bring flexibility, they are thin and inherently fragile. They are either mechanically formed or hydroformed from thin tubes, or assembled by welding a series of individual annular rings.

The design of bellows is treated in the general codes for pressure vessels but a specific code has been issued by the manufacturers, The Expansion Joint Manufacturers Association, Inc. (EJMA) [10], recognized as the authority on metallic bellows type expansion and a project norm pr-EN 14917 [11] was recently published by CEN.

Bellows are designed to withstand a given number of cycles of axial expansion/compression over the expected life of the system. They accept an angular movement but large offsets drastically decrease the fatigue limit. A double bellows 'à la cardan' (two bellows with a tube in between) is the recommended solution for the latter case if space exists. If the neighbouring tubes are not correctly supported, the bellows may buckle immediately or after cycling.

3.6 Special shapes

The imagination of the designer is without limits. Any shape can be designed and analysed with the available tools. But one should be careful with the analysis of the results, in particular with the interpretation of the local stresses (true or generated by the FEM mesh). Curved surfaces are preferable to flat panels wherever possible.

However, the inherent difficulties of manufacturing should not be forgotten. Major progress in extrusion technology now permits fancy shapes with multi-channels. Welded tubes could also be ring-stiffened to compensate for a thin wall or for a large width leading to large deflections.

4 Manufacturing and assembly

4.1 Machining and sheet metal work

Materials for manufacturing are available in various states: raw products like blanks or sheets, or semi-finished products like extruded elements (aluminium, copper), moulded, forged, or sintered (ceramics).

The choice is usually founded on cost but the final quality in terms of vacuum may be disturbed by the manufacturing techniques. Defects due to impurities internal to the material should not provoke leak-through and elaboration techniques properly handled help with that. Forging, extruding and laminating will squeeze the impurities but also enclose them. Machining will open them with a risk of leak, even with a good quality material. Laminated metal sheets will usually remain leak-tight except in the case of large deformations due to forming (e.g., deep drawing, 180^{o} folding) or in the heat affected zones next to the welds.

4.2 Joining techniques

Joints are the main source of leaks in vacuum systems.

The first question to answer before choosing the assembly technique is: Is this assembly dismountable and, if yes, how often? This will help to choose knowledgeably between flanges and permanent sealing like welds. The cost in terms of money and space of flanges should be compared to that of a welding and subsequent cuttings and reweldings: parts, tooling, accessibility and operation costs.

4.2.1 *Flanges*

Flanges are industry standards available on the market. However, metal-sealed flanges can be developed for specific needs. The main parameters for their design are the strength of the material to withstand high forces for bolting or clamping, and the quality and hardness of the surface where the seal is positioned. The seal itself should keep its overall rigidity (elastic behaviour) while its surfaces in contact with the flanges should plastify to enforce leak-tightness.

4.2.2 *Welding*

Welds are a source of impurities and defects. Therefore, they should be carefully managed. Welding techniques will not be treated in detail here but hints in order to avoid potential problems are given.

The first point, obvious but sometimes forgotten because of the weight of other arguments, is the weldability of the material. To fulfil their role of mechanical resistance, the welds should be designed and executed according to the rules of the construction codes. Depending on the requirements, a reduction factor (0.85, 0.7) is applied in the calculation of the stress level and it is therefore recommended to avoid localizing a weld in a highly stressed zone.

But specific rules should be applied to high vacuum chambers to avoid contamination and virtual leaks generated by pockets. The welds should be performed on the vacuum side and trapped volumes between two welds are forbidden. Filler metal is not recommended. Grooves help to minimize heat propagation along the walls and can be useful in case of subsequent cutting and rewelding. Crossing welds lead to a remelting of the bath creating defects. Figures 4 and 5 present the typical weld configurations for vacuum components.

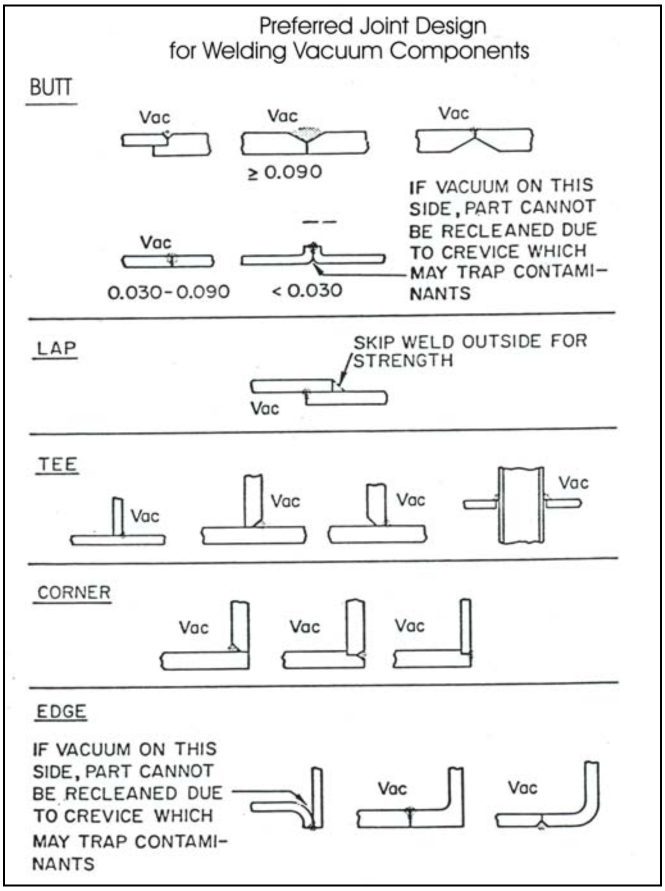

Fig. 4: Typical weld configurations for vacuum components

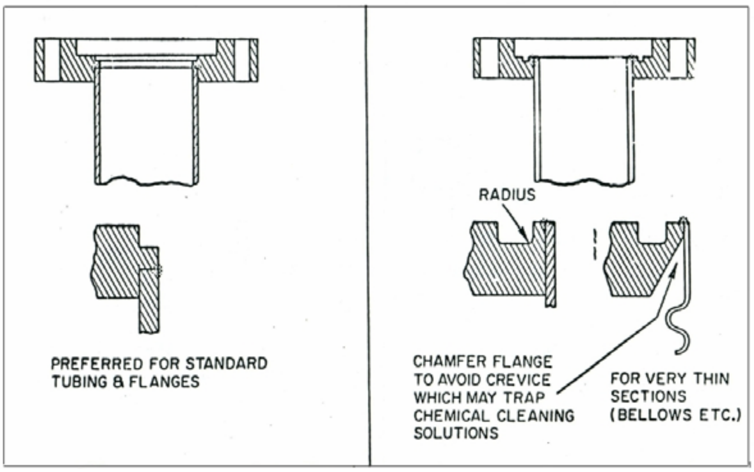

Fig. 5: Typical weld configurations for vacuum flanges

The preferred and most used technology is the Tungsten Inert Gas (TIG) welding. A very good inert gas (argon) protection is a prerequisite. Electron beam welding is another solution but it is not as flexible owing to the need for a vacuum envelope. And in case of thin shells, plasma welding is recommended.

Finally, one should remember that a good mechanical preparation of the parts to be welded is the key to success and that it is easier to weld in the workshop than *in situ* and the quality will be in accordance.

Whatever the techniques and the quality, no more than 99% of a series of welds will be leak-tight. Visual inspection must be systematic and X-rays are highly recommended if not compulsory.

4.2.3 Brazing

Brazing is an expensive solution which requires a furnace filled with a protective gas and jigs to keep the parts in position during the thermal cycle. It is often the only solution to join dissimilar metals or ceramics together. But the design of the interfaces to be brazed should be done according to strict rules taking onto account the expansion of the materials to allow the brazing to flow through the gap. The surfaces are etched before and a high-quality cleaning after brazing is important: one classical problem is the appearance of corrosion on stainless steel following a deficient cleaning of the chloride-based flux.

4.2.4 Gluing

Gluing is quoted here for completeness. Configuration of joints is similar to the ones used for brazing but the curing temperature is lower and even ambient. Degassing of glue joints is a problem, even for high-performance glues (epoxies) which are commonly used to repair leaks. There is still room for development of gluing of vacuum parts.

4.3 Cleanliness

Cleanliness of the delivered parts is essential to minimize outgassing. Cleaning can be performed through well-known processes which should be compatible with parts (materials, temperature, abrasion). But it is preferable to avoid polluting the parts during the fabrication, for example, to avoid machining with silicon oils difficult to remove. The last step of cleaning is to fully empty and dry the parts; the design should take that into account by suppressing zones where puddles will remain and avoiding closed volumes.

4.4 Ease the detection of leaks

An important and sometimes painful step in the commissioning of a vacuum system is leak detection. Simple actions will ease that work: provide access to the vacuum chamber, in particular to the joints (helium spraying, clam shell), avoid virtual leaks by suppressing closed volumes like bolts.

The time-of-flight technique will be used for large chambers: provide an easy way for helium to flow through radially in order to minimize the perturbation when measuring time of flight over long distances.

5 Quality assurance

A good design is the first step for good quality but it might be entirely spoiled by bad quality manufacturing. What is required should be clearly specified in the technical specification and in the drawings, using international standards. All the steps of the procurement, manufacturing, and assembly should be detailed beforehand and controlled according to agreed procedures. The construction codes contain specific chapters on this subject. But, in any case, the minimum requirement for choosing a manufacturer is that he be certified ISO 9001:2000, even if this is not foolproof.

To include regular inspections at the premises of the contractor either by your technicians and/or by an accredited inspection body could be considered a quite heavy workload but it is the only way to obtain the required quality. Look in particular at the material used versus the one specified, at the tolerances of the parts versus the manufacturing drawings, at the procedures and at the cleanliness.

6 Conclusion

Designing a vacuum chamber should not be very complex and a systematic approach will help to get what you expect with good quality at the right price.

Acknowledgements

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